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**HIGH ANGLE OF ATTACK POSITION SENSING
FOR THE SOUTHAMPTON UNIVERSITY
MAGNETIC SUSPENSION AND BALANCE SYSTEM**

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S U M M A R Y

An all digital five channel position detection system is to be installed in the Southampton University Magnetic Suspension and Balance System (SUMSBS). The system is intended to monitor a much larger range of model pitch attitudes than has been possible hitherto, up to a maximum of 90° angle of attack. It is based on the use of self-scanning photodiode arrays and illuminating laser light beams, together with purpose built processing electronics.

The principles behind the design of the system are discussed, together with the results of testing one channel of the system which was used to control the axial position of a magnetically suspended model in SUMSBS. The removal of optically coupled heave position information from the axial position sensing channel is described.

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1. INTRODUCTION

1.1 Background

The potential advantages of the magnetic suspension of wind tunnel models have repeatedly been described since the first wind tunnel magnetic suspension and balance system (MSBS) was reported in 1957. Aside from the elimination of support interference, the ability to rapidly and conveniently alter model position and attitude is seen as offering a considerable improvement in wind tunnel productivity.

All existing magnetic suspension systems including that at Southampton University, are capable of suspending models over relatively limited ranges of pitch and yaw excursion - typically $\pm 15^\circ$. However, as a recent solicitation of opinion in the U.S. Aerospace Industry showed (1), there is considerable attraction in any future large MSBS having the capability to suspend models at much higher incidences - up to 90 degrees if possible. Such regimes are of considerable practical interest but tend to be analytically intractable.

Work is underway at Southampton University to demonstrate control of five degree of freedom stabilised model over a nominal 90 degree pitch angle range and in the low speed wind tunnel of which the suspension system is a part. This report briefly discusses the deficiencies in the Southampton MSBS (SUMSBS) which at present prevent suspension at high incidences and describes one area of development - that in the optical position sensing system - that will help overcome these drawbacks.

1.2 Previous Work

Three main problems connected with suspension at extreme attitudes have previously been described (2):

- * identification of electromagnet (E/M) array geometries and configurations capable of generating, via fields and field gradients, forces and torques on the model in required senses and magnitudes over the full range of model attitudes.
- * synthesis of control algorithms capable of accommodating large changes in model aerodynamic characteristics and magnetic couplings from the electromagnets.
- * design of position sensors to monitor wide ranges of model motion.

Previous analytical and experimental work concentrated on the first of these areas of difficulty (3). Comparison of the force and torque generating capabilities of two MSBS configurations was made, one of which corresponds to SUMSBS in its present form. It was shown that the high incidence capability of the design is fundamentally limited only by a diminishing availability of sideforce, falling to zero at 90 degrees incidence.

To verify these results a model was flown at angles of attack around 40 to 60 degrees. Detailed changes were made to the control algorithms and the optical position sensing system (see below for description) moved to a 50 degree pitched position in sympathy. A rotation from 0 to 60 degrees was not possible. Hence the second and third problems above were avoided.

The current work is directed towards allowing a suspended model to be controlled between zero and ninety degrees pitch angle. This requires all three areas of difficulty to be tackled simultaneously. Simple modifications to the electromagnet array of SUMSBS will make sideforce available at ninety degrees incidence (see Figures 1, 2). It should be noted that this biasing of the Figures 1 and 2 sideforce field to a positive incidence maxima means that the sideforce capability diminishes to zero at minus 60 degrees incidence. The design of suitable control algorithms is continuing and is not discussed here. What follows is a description of the position sensing problem and of the new optical system which is being fitted to SUMSBS.

2. THE LARGE ANGLE POSITION SENSING SYSTEM

2.1 System Requirements

The MSBS is a statically unstable system which requires feedback control to maintain an aerodynamic model in a fixed position and orientation. The response in position of the model to electromagnet current demands must continually be monitored in order to close the control loop. An optical position sensing system is used in the Southampton MSBS. This is based on a light beam shadowing technique, where the model partially obscures shafts of light falling on image detectors.

At present there are five pairs of light sources and sensors, so that five degrees of freedom may be detected (note that a sixth pair - used to measure rolling motion - has in the past been fitted). The light sources are uncollimated and the detectors simple photodiode/condensor lens combinations which yield analogue voltages. These are digitised by 16 bit A/D units for processing by the control computer. The four main beams use tungsten lamps as their sources, whilst the axial sensor use a low power laser beam, expanded in one plane by a cylindrical rod lens.

For the analogue shadow detection system to function one model edge must be visible to each of the sensors at all times. If a second (opposite) edge was seen by any sensor its output would cease to change with continued motion and the system would fail. Hence, the maximum available model translational motion is the same as the sensor field of view. Rotational motion is detected by the difference in outputs from pairs of sensors fore and aft of the model centre of gravity. At present the available pitch (and yaw) angle range is about 30 degrees. If the existing system were to be extended to give a 0 to 90 degrees capability the light beams and condensor lenses would have to be considerably enlarged and the whole arrangement inclined by 45 degrees. The resulting configuration is feasible but has not been pursued because of the problem of adequate calibration.

Since the location of the beams and sensors of the present system is not precisely known and the detector outputs are non linear, the present optical system must be calibrated before use. This is accomplished by traversing a dummy model in all required directions and rotations across the field of view of the sensing system. Curves of sensor output against position can thus be obtained. This is necessarily a difficult and time consuming process. Although high resolutions of position can be obtained - of the order of one thousandth of an inch or better - non-linearities mean that it is difficult to incorporate them into the control program in such a way as to permit user demands of the form (for example) 'move in a heave direction by +2mm from the present position'. Information relating to the sensor outputs for every model position and orientation would have to be obtained and stored for access by the control program. Complete calibration in this way has never been attempted. For maximum productivity of an MSBS a better calibration technique is required.

It has been evident for several years (4) that more modern optical sensors than analogue photodetectors are available and that these could be incorporated in an MSBS to produce a more flexible sensing system.

Such devices include linear and area monolithic photodiode arrays of various design and manufacture. These are now widely used in application such as star trackers and bar code readers. The essential feature of these devices is that they consist of a large number of nominally identical photodiodes evenly spaced on a single package of compact dimensions. This offers the possibility of obtaining position information of an object in terms of numbers of (for example) illuminated and non-illuminated photodiodes. Hence, these devices are known as digital sensors. They are more naturally adapted for use with a computer based control system since they obviate the need for A/D converters.

The simplest way of incorporating this technology into a MSBS is to use linear arrays in place of the analogue photodiodes. A condensor lens is not necessary provided that the array length is

comparable with the required model motion. Both linear and area arrays are available built in to cameras, but for reasons of cost and space limitation, the option of using these with SUMSBS has not been investigated in detail. Hence, the new sensing system uses five linear arrays illuminated by five light beams in place of the existing analogue detectors.

It may be noted that a self scanning photodiode array has previously been used to monitor the heave motion of a model in suspension in SUMSBS*. However, the illumination system was a simple tungsten lamp and lens combination, and the digital sensor output was converted via a D/A converter into an analogue voltage which could then be assessed by the existing A/D system. Hence, the potential inherent in the use of a digital signal was wasted. The processing electronics to be used with the new sensing system are described in Section 2.4.

* reported as 'Photodiode Array Position Sensing of a Model in a Magnetic Suspension Wind Tunnel', by R H Moore, 1981, (Southampton University, Dept of Electronics).

2.2 Configuration and Capability of System

The detector device chosen for the large angle position sensor is the Reticon RL1024G self scanning photodiode array which consists of 1024 silicon photodiodes mounted on a single chip at an even spacing of 0.001" and protected by a glass window. Each device is illuminated by a collimated beam of Helium-Neon laser light. The magnetically suspended model intersects the light beams and its location is measured in terms of the light to dark transition of each array output. Provided that the model diameter is less than the sensor length, the maximum linear motion of the model is equal to just less than the sensor length plus the model diameter. This is because unlike the analogue sensor, more than one model edge can be simultaneously viewed by a single detector array.

The arrangement of the five light beams and the detectors is shown in Figures 3 and 4. If typical geometrical dimensions are specified, the translational and rotational capabilities of the system can be deduced. These are summarised below for a typical 18mm diameter cylindrical model:

Perpendicular Separation of Double Beams	46mm
Cross Angle of Beam Pairs	70.53°
Pitch Angle Range at zero degrees yaw angle (datum heave, slip, and axial position)	-15°/ + 105°
Yaw Angle Range* at + 45° pitch angle (datum heave, slip, and axial position)	+/-10°
Yaw Angle Range at -15°/ + 105° pitch angle (datum heave, slip and axial position)	+/-6°

Yaw Angle Range* at 0°/ + 90° pitch angle	+ /-10°
Slip Motion Range* at 0°/ + 90° pitch angle	+ /-9mm
Slip Motion Range* at 45° pitch angle	+ /-9mm
Heave Motion Range at 0°/ + 90° pitch angle	+ /-13mm
Heave Motion Range at + 45° pitch angle	+ /-20mm

* denotes limited by tail of model moving out of axial motion light beam.

It can be seen that, because of the diamond shape of the intersection areas of each of the two pairs of main beams, the maximum available motion in each of the degrees of freedom other than pitch occurs at the 45° angle of attack.

An inherent limitation of the system is that a pure pitch rotation between the system limits is not possible without some axial translation. This results from the linear motion which can be seen by the axial sensor being less than the distance swept out by the tail of the model during such a rotation. A longer axial sensor (e.g. RL 4096) would remove this problem, but at a significantly higher cost. Instead two means of effecting the 0 to 90 degree rotation may be employed. Firstly, the axial sensor can act in 'position fixing' mode as the model pitches; that is, it acts to oppose any apparent change in axial position. This means that the magnet array responds by producing an axial force simultaneous with the pitching moment (the existing analogue axial sensor functions in this manner).

Alternatively, the axial sensor can be 'decoupled' from the pitch rotation, so that it does not respond to any change in its output if this results from pitch attitude change. Pure pitch rotation is thus produced until the tail of the model has swept almost the full length of the axial sensor. An axial motion is then required to return the tail of the model to the opposite end of the sensor before pure pitch motion can continue. To accomplish the 90° rotation, one positive translation is required at about + 30° and one negative translation at about + 60°. The problem of decoupling is discussed more fully in Section 3.6.

To make full use of the potential for inherent calibration offered by digital sensors and the shadowing technique, it was decided at an early stage to use collimating light beams to illuminate the sensors. This means that a translation of (say) 10mm is interpreted by the sensing system as being of exactly this amount irrespective of the separation between the model and the detectors.

In principle this can be achieved to an accuracy dependent only on the resolution of the detector. For the RL1024G this implies a position keeping capability of one thousandth of an inch, and since the required pitch angle range is one hundred and ten degrees, the average angular resolution is approximately one tenth of a degree.

However, ignoring for the present the axial motion channel, one degree of model freedom is not measured by one individual sensor, but instead is obtained by combination of outputs of the four main detectors. For example, pitch attitude information is obtained by adding the model position measured by the forward pair of sensors and subtracting the sum of the outputs of the aft pair. The consequence of this is that not only must the light beams be collimated, but also their separation and crossing angles must be known. If the complete geometry of the beams is determinate, then it is possible to predict the edge location of a given model for any position or attitude in terms of the number of illuminated or darkened photodiodes for each of the four arrays. The measure of the model's location in this form is termed its pixel count.

A simple Fortran program (PIXEL) has been developed which calculates the edge location of a cylindrical model in terms of pixels for any chosen position or attitude. It is planned to incorporate this information into the MSBS control program in the form of look up tables so that a user demand in literal form ('move in pitch attitude from 10 to 22 degrees') can be interpreted by the control program as a change in the pitch pixel count. In practice this ideal concept is complicated by considerations of optical distortion and edge diffraction effects. These are discussed in Section 3. Also since each sensor may see either one or two model edges, the pixel count for one position and orientation is not unique, but may exist in several forms. Computer logic is thus required to carefully distinguish incoming data from the sensing system, and relate it to the user input position demands.

2.3 Illumination of Position Detectors

The requirement to produce highly collimated and precisely aligned light beams to illuminate the detector arrays has dictated the selection of optical equipment for the new position sensing system. The four main beams originate in a single medium power laser from the existing analogue axial system. Lasers have been used since they can readily be expanded and collimated by lens systems and offer cost advantages over collimated tungsten or arc sources. However, the use of coherent light can produce interference effects from two surface optical components (e.g. lenses). Use of suitable anti-reflection coatings can reduce these problems but their presence has been noted in experimental testing.

The laser beams are expanded and collimated by respectively short and long focal length cylindrical lenses, with fine control of separation and rotation. The main beam system uses an 8mW multimode laser to give a more even illumination than is possible with a Gaussian laser beam. The collimated beam is fed into a system of cube beamsplitters and right angle prism mirrors to produce four separate beams with independent positional and angular control commensurate with the array resolution. Fixed mirrors deflect the main beams across the test section to strike the sensors normally (Figure 4). The sensors are fitted to mounts which permit fine positioning in the

two directions perpendicular to the beams, as well as rotation about the normal to the sensor face. The axial beam is incident at 45° to the axial sensor because there is insufficient room between the lower E/Ms and the wind tunnel test section to permit an inclined installation.

In order to carry out the beam alignment procedure outlined above, a target device must be installed in the test section. This is a precisely machined unit with parallel entry and exit apertures for the beams, together with pairs of target rods to allow setting of the beam crossing angles.

2.4 Photodiode Array Control System (PACS)

At present, operation of the Southampton MSBS is under the control of a PDP11/84 mini-computer which interrogates the position sensing system once per program loop, via the A/D system, in order to carry out the model stabilisation and determine E/M current output demands. To make full use of the data available from the digital sensors, new interface electronics have been developed.

Each cell of the arrays consists of a photodiode and a dummy diode both with an associated storage capacitance (5). The diodes are connected through MOS multiplex switches to video and dummy recharge lines which are common to all the cells. The scanning circuit is driven by a single-phase TTL clock with a periodic TTL start pulse introduced to initiate each scan. The cell-to-cell sampling rate is the clock frequency, and the total time between line scans is the interval between start pulses. During this line time, the charge stored on each photodiode is gradually removed by photocurrent. The photocurrent is the product of the diode sensitivity and the light intensity (irradiance). The total charge removed from each cell is the product of the photocurrent and the line time. This amount of charge must be replaced through the video line when the diode is sampled and reset once each scan. Hence, information as to the amount of light falling on each diode can be obtained. By differentially reading out the video and dummy cell lines, switching transients can be removed.

The output charge is proportional to the product of light intensity and the line scan time up to a certain fixed level (the saturation exposure). The mode of operation used in this application is to saturate all the diodes of each array with an approximately uniform light source. The required intensity of illumination thus increases as the integration time is reduced (scanning frequency increased). Using data supplied by the manufacturers the saturation intensity for a given frequency can be calculated (see Appendix1).

Reticon supplied circuitry provides as an integrated sample and hold type video signal from each array together with information as to:

- (1) the offset of a shadow edge from the datum of the first diode,
- (2) the state of illumination up to the edge (light or dark),
- (3) the width of the shadow (if a second edge is present).

In addition, control logic can indicate:

- (4) the occurrence of a second edge,
- (5) the occurrence of an anomalous third edge and
- (6) system errors that may invalidate values returned.

The purpose of the new electronics (Figure 5) is to transfer this data on demand to the controlling computer. PACS has been designed as a co-existent module with the current analogue sensing electronics. A microprocessor (Z80CPUA) is used to co-ordinate 16-bit counters, each of which stores the pixel count of one event (transition). Several additional operations are easily implemented. These include software control of photodiode clocking rates, video-binary threshold control, direct measurement of low frequency content (possibly for use in auto-setting thresholds and sensor problem detection), data buffering and basic data pre-processing. The microprocessor also undertakes a series of diagnostics on power-up.

Up to six diode arrays can be accommodated, although only five are planned at present. One is designated the master drive board and provides a clock-derived synchronising signal to enable predictable scan status for all the arrays. Communication of data is achieved through a set of commands from the control computer which requests appropriate microprocessor activity.

PACS is now assembled and is undergoing software development. The operating principles have been verified by use of a single channel providing axial position information in co-operation with the existing analogue system for slip, heave, pitch and yaw attitude data. This is discussed in Section 3.

3. EXPERIMENTAL WORK

3.1 Introduction

Practical activities directed towards installation of the large angle position sensing system has been in two areas: determination of the absolute capabilities of the collimated laser beam/SSPD array combination and demonstration of one complete optical and electronic channel of the planned system.

In investigating the characteristics of the beam and sensor, various real optical considerations were revealed which may limit the achievable resolution of the new optical system, although not invalidate the general principles.

The demonstration of one sensor channel involved the successful suspension and operation of a standard test model, a calibration of the array, and a comparison of performance with the existing analogue sensor.

3.2 Sensor Characteristics

For the testing of the digital array, a train of optical components was used to illuminate an RL1024G sensor. It consisted of a 1mW He-Ne laser, a 4mm anti-reflection coated expansion lens, and a 250mm focal length cylindrical collimation lens designed to produce a 32mm wide beam of light. The sensor output was made accessible to the SUMSBS PDP 11/84 computer via PACS. A Fortran/Macro 11 program was used to show in real time data in the form of distance in pixels from start of scan (pixel 0) to a first transition (either light/dark or dark/light) and then the span to a second transition. Adjustment of the transition threshold voltage was by a potentiometer on the PACS electronics card. A storage oscilloscope and analogue plotter was used to obtain recordings of sensor output signal profiles.

Ideally a transition event would produce a step change in sensor output, taking only two pixels to occur. In reality at any finite distance from the face of the sensor, an object will produce a transition edge ('modulation transfer function' -MTF) spread over several pixels, which may vary as the object is moved across the sensor. In particular, this type of sensor is quoted in manufacturer's data as having a non-uniformity of sensitivity between diodes of up to $\pm 14\%$. Thus, if the MTF is broadened by some other effect, and the threshold level is fixed, the apparent width of an object will vary for different locations and the calibration of distance to the first event will not be perfectly linear. The MTF is in fact broadened by diffraction effects.

For the situation of relevance here - that is, an edge in a beam of collimated light - near field of Fresnel diffraction theory is used. This is described in Appendix 2, but the main results may be summarised as follows.

Moving from full illumination into the shadow of the object, the irradiance distribution consists of a series of oscillations about the mean full value, which increase in amplitude before dropping monotonically to zero. The width of the MTF, measured in terms of the number of pixels, increases from zero when the object is directly in front of the sensor to tens of pixels at model/sensor separations representative of the full system. The true geometrical location of the object's edge corresponds to the pixel where the illumination is one quarter of the full value. Thus if the

position sensing system is to be used as an absolute measuring device, the threshold should be set at the corresponding output voltage level.

However, the illumination of the sensor is such that it is completely saturated, and the diffraction fringes and the full illumination level is not directly seen, but is 'lost' in the even saturation output level. The one-quarter level cannot be deduced by examining the output profile unless some curve fitting procedure is used. This has not yet been pursued because a simpler solution is to measure the target object mechanically, and record the discrepancy with the measurement from the optical sensing system. It may be noted that this difference will only remain fixed if the model/sensor separation is constant, but it was found that with care the threshold level could be set to give constant measurements close to the true object size. Also, if the threshold level does not correspond to the one quarter illumination level then the system is set up to give a constant object width measurement, the light rays are not parallel; hence, the term 'collimated' light beam is always used.

3.3 Collimation Tests

To examine the extent to which the light beam and sensor system could be used as an absolute measurement device, the test beam was collimated by first placing an object of known size directly in front of the sensor and recording its width in terms of pixels. To check that the measured width was consistent for any lateral position on the array the object was traversed across the sensor face using a screw drive driven via a set of gears from an electric motor. The procedure was then repeated with the object placed 150mm from the sensor, the focussing of the collimation lens being adjusted until the same object width measurement was obtained. Table 1 shows typical results.

For the first case (model very close to array) the measurements are highly consistent, as would be expected, apart from the cases close to one end of the sensor. This is judged to be for reasons of pixel non-uniformity. The manufacturer's performance specifications exclude the first and last two pixels, suggesting that their characteristics might be expected to be significantly different from the majority of diodes.

The collimation is not so good for the situation where the model is at a distance from the array representative of the system installed on the MSBS. Nevertheless, without excessive care spent in optimising the optics, the width measurement is accurate to within ± 2 pixels.

Note that the measured object width is 5 thousandths of an inch greater than the true size. This is because the transition threshold level was set higher than one quarter level mentioned above. Although this level could be set it was found that the distance to first edge and object width

readings became unreliable, flicking over a range of a few pixels about a mean value, or falling to zero. Reasons for this behaviour could not be found by examining the output oscilloscope trace, and so are probably associated with small instantaneous optical defects such as dust particles producing short lived, spurious edge events. The collimated beam/sensor combination is vulnerable to any permanent damage to optical components such as from scratches, which may cause system failure. However, compared to the analogue sensors, the availability of the output video signal allows the presence of such defects to be readily detected - gradual decay in performance due to build up of dust has been a major problem with the analogue sensing system. Also, diffraction around a small particle can fill-in the missing light in the distribution detected by the digital array, unless the threshold is set very low.

It should be noted that the discrepancy between the actual and measured object widths must be incorporated in the pixel count information used by the control program to position the model in response to user demands, if the precalibration technique is to be justified.

3.4 Installation and Testing of Digital Axial Sensor

The optical components described in Section 3.2, together with the adjustment mirrors shown in Figures 3 and 11 were fitted to the Southampton MSBS and used to illuminate an RL1024G sensor installed in place of the existing analogue axial sensor. The analogue photodetectors of the four remaining control channels were left unchanged. Figure 6 shows the sensor output with and without laser illumination. Background illumination was less than 5% of the saturation level.

The introduction of a small test target (a brass rod) supported by an adjustable mount placed in the MSBS test section immediately showed that the resulting two transition edges were markedly different from each other (see Figure 7). The first edge - that is, the one on the downstream side of the object - has a series of what are evidently interference fringes. The other edge is a well defined diffracted transition of the type described previously. It appears that the poor quality of the first edge is caused by the acute angle of the incident beam on the sensor causing interference between the light passing directly through the sensor window and that reflected within it. The effect on the output data from the sensor was to produce an object width measurement which could change suddenly from the correct value to a small value (2 to 6 pixels) as one of the fringe spikes passed through the threshold level. As a result it was impossible to collimate the beam to an accuracy greater than ± 5 pixels. However, this is not seen as a major failure because the axial sensor is not required to be used in an object width measuring mode: only the distance to the first edge is required and the sensor threshold could be set to give a consistent value of this quantity. The four main beam/sensor pairs should not suffer from this problem because the beams will be normal to the sensor window.

With the laser beam approximately collimated, the incident angle of the beam on the sensor was set using a simple alignment device. This consisted of a pair of pivoting arms connected at their lower end by a target object and having at their upper end a mounting for a second, identical target object. The arms could be locked at any desired angle against the supporting block which was itself held in the MSBS test section by a pair of projecting rods attached to the MSBS main frame.

The light beam passed between the arms to strike the lower object, and the resulting width measurement was recorded. The second upper object was introduced and the beam angle adjusted using the lower tilting mirror until the combined shadow width of the two objects fell to its minimum value, indicating that they were directly in line. Thus, the desired beam angle was set at 45° relative to the alignment device.

3.5 Sensor Calibration

To check the linearity of the sensor output, a calibration of the axial sensor was carried out in situ. This was accomplished by using the dummy model calibration equipment already used with the MSBS. A precise copy of the outline of a magnetically suspended model is held in the test section by a sideways projecting beam which is supported by a pair of translating slide mounts and a rotating table. These allow very fine settings of heave and axial position and pitch attitude to be measured. Figure 8 is a calibration line obtained by traversing the dummy model over the full length of the sensor, whilst Figure 9 shows a corresponding curve for the previous analogue axial sensor. The outstanding advantage of the digital sensor over the analogue type - its linear calibration - is thus demonstrated.

3.6 Suspension of Model

To permit suspension of a model with the aid of the digital axial sensor modifications to the MSBS control program were necessary. These included the deletion of the A/D routines used to access the analogue axial sensor. PACS commands were added to disable the A/D system to allow the reading of the two counters containing the digital position data, followed by the re-enabling of the A/D system. A problem which was revealed was that although both the PDP 11/84 computer and PACS are capable of rapid operation execution times, the input/output port on the computer was not able to respond fast enough, resulting either in I/O demands not being performed, or incorrect operations occurring. In particular, on switching on the electromagnet power supplies, a full current was instantaneously demanded from one of the electromagnets. It transpired that the E/M output operations were located immediately after those of the axial sensor in the control program listing, and hence were corrupted. Artificial delays were introduced into the control program to overcome these difficulties.

Suspension of a standard model was readily achieved, although brief but violent flicks in position occurred about once per minute. This was judged to be because of the sensor output instantaneously falling to zero, as noted in the initial tests (3.2). By introducing an algorithm in the program to discard position data and re-use the previous axial measurement if the change in edge location in one program loop was greater than 100 pixels, the problem was eliminated. Figure 10 shows a trace of the video signal with the model in suspension. As anticipated the transition edge is affected by optical interference. Figure 11 illustrates an Alnico cored calibration model magnetically suspended in SUMSBS with the digital axial sensor and illuminating laser beam.

By recording 256 successive samples of position sensor information (which corresponds to one second of data for the control program loop rate used) the ability of the digital sensor to hold a model to a specified axial location was investigated. The data showed that the pixel count was consistently within ± 1 pixel of a target. For example, with a requested position of 512 (that is 512 pixels to the threshold transition) the output drifted gradually between 511 and 513 pixels and back again in a slow oscillation of a few Hz which was also evident in the position data from the four main analogue sensors.

Because of the inclined axial sensor beam, any heave motion is coupled to the axial channel; that is, an apparent axial position error appears (Figure 12). The control system responds by removing the error, which results in an axial motion combined with the demanded heave transition. An approach to decoupling the axial sensor was therefore demonstrated as an additional algorithm in the control program. The principle is to first calculate the change in the measure of vertical heave position (the sum of the outputs of the four main sensors) which has occurred between the present and previous program loops. The accompanying change in axial sensor output is proportional to this quantity, and if the constant of proportionality - the heave/axial coupling factor - can be found the expected change in axial sensor output can be subtracted as an offset, so that only true axial motion remains. The factor varies with model pitch angle, falling to zero at 45° incidence before increasing again.

For the ultimate five axis digital sensing system, the linear sensor calibration means that the coupling factor is determinate for a given configuration of light beams. However, for the non-linear analogue sensors the coupling factor changes also with the heave position. Thus, it was decided to decouple the axial sensor for one datum position only and for the 'worst case' incidence - zero degrees - to demonstrate the principles involved.

To find the coupling factor, a dummy position calibration was performed in the heave direction about an arbitrary datum position. Using an existing analysis technique the average slope of the four main sensor calibrations was found (the change in output per unit movement). By dividing

this into the corresponding gradient of the axial sensor calibration, the coupling factor was calculated and then incorporated into the control program.

The resulting motion in response to a heave demand was a more pure translation, with the final axial sensor reading greater or smaller than the starting value, depending on the sign of the requested movement. There was however some visible overshoot in the axial motion, indicating the different dynamic characteristics of the two degrees of freedom. Figures 13 and 14 show data for a typical heaving oscillation with the actual position compared with that required by multiplying the corresponding heave position by the coupling factor.

Applying a sine curve fitting analysis to the two sets of data produced the following results:

	Required Output	Achieved Output
Mean position (pixels)	512.05	512.22
Oscillation amplitude (pixels)	25.53	27.39
Oscillation frequency (Hz)	2.505	2.494
Phase Angle (rad)	0.0	0.128

Since the decoupling technique involves responding to a positional error, a phase difference between the ideal and actual sensor outputs would be expected. Knowing the looping frequency of the control program (256Hz), the phase error can be deduced to be equivalent to about 2 program loops. There is also evidence of some non-linearity in the sensor output as a result of the impure transition edge with its interference fringes. Figure 15 shows the difference between the ideal axial sensor output and that actually achieved. There is evidence of an oscillatory function with the error in output being the most around the datum heave position, when the rate of motion is at its greatest. Further development of the sensor and algorithms will be required to fully demonstrate the decoupling, since only one small sample of data was examined during the period of testing, but the results are encouraging.

An alternative decoupling technique which would eliminate the phase error in the axial channel would be to demand an axial motion (in terms of the position sensor axes) together with the heave motion demand. This will be studied for future implementation.

It should be noted that pitch motions were also coupled via the inclined sensor beam to the axial channel. Modifications to the control program to produce only pure pitch rotations were not made, but the principles involved are identical to those described above for the heave/axial channel coupling.

4. FUTURE WORK

Following the suspension tests with the digital axial sensor, the optical equipment used to illuminate it has been removed and a vertical laser beam system re-installed to permit the work on dynamic calibration to continue. However, the demonstrable advantages of the digital sensor have resulted in it being retained for this purpose, together with the non-collimated beam.

Before the installation of the full five degree of freedom sensing system proceeds, the changes to the control program to account for the varying model/electromagnet couplings must be implemented. Also the lateral electromagnets will be re-located in the skewed configuration with new support frames.

Suspension of a model using the sensing system will begin at zero degrees angle of attack before opening up the pitch angle range to the intended full 100°. Oscillations must be demonstrated for dynamic calibration purposes.

Modifications will have to be made to the test section to permit wind tunnel testing to be accomplished with the new sensing system. In particular, the section windows will have to be of a high optical quality to limit reflection and interference effects on the beams of light reaching the sensors.

The large angle position sensing system described here is not seen as a final solution to the general position sensing problem of magnetic suspension systems. It is limited in its performance in a number of ways:

- * inadequate angular resolution (only about 0.1 degrees)
- * confined to axisymmetric models (a five degree of freedom system)
- * prone to failure as a result of optical degradation (owing to use of collimated light)
- * has expanded pitch angle range in positive sense only
- * does not have expanded yaw angle range

As at present planned, the pre-calibration of the sensing system by precise beam alignment is only applicable to models of cylindrical shape. However, with a more sophisticated program for geometrical analysis, this calibration technique could be used with models of any general shape, especially if combined with a suitable rolling motion sensor and control channel.

In summary, further study will be required to identify optical position sensing techniques applicable to any further large MSBS with extreme angle techniques applicable to any further MSBS with the capability for extreme angle suspension capability. However, the new sensing

system described will permit high angle suspension for the first time as well as being an essential tool in developing the novel control system features needed for such a capability. The testing of one sensing channel, as described here, has assisted in preparations for the installation of the complete system, which will begin shortly.

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APPENDIX 1

CALCULATION OF SATURATION LIGHT INTENSITY FOR RL1024G SENSOR

From information supplied by the manufacturers, an estimate of the light intensity required to ensure saturation of an RL1024G photodiode array can be made.

The responsibility of the device is defined as the product of the absolute diode sensitivity and the pixel area.

$$R = S.a \text{ in } A/W/cm^2$$

Where the absolute sensitivity S is dependent on the wavelength of the incident light and on the characteristics of the array window, and the pixel area a is specified for the particular array in question.

The saturation exposure is the saturation charge divided by the responsivity

$$EXP_{sat} = Q/R \text{ in } J/cm^2$$

Now the energy required to saturate one diode is:

$$\begin{aligned} E &= EXP_{sat}.a \\ &= Q/S \text{ Joules} \end{aligned}$$

The power for a scan time of t is:

$$\begin{aligned} P &= E/t \\ &= E.f/n \end{aligned}$$

where f is the scanning frequency and n is the number of diodes in the array. The total power input in one complete scan of the array is thus:

$$\begin{aligned} P_{tot} &= nP \\ &= E.f \\ &= Q.f/S \end{aligned}$$

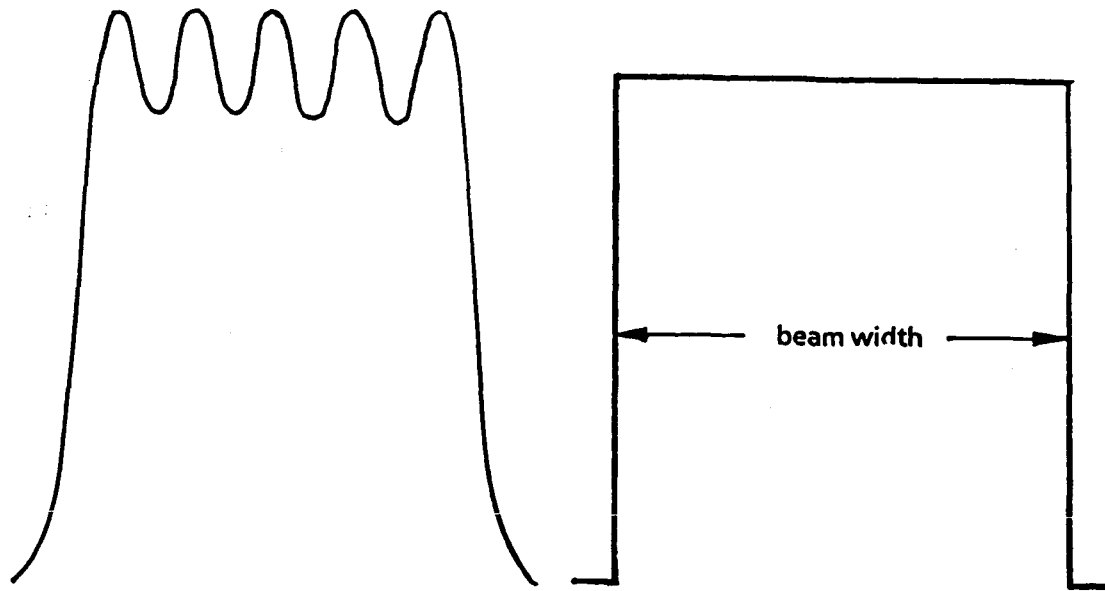
For the frequency of the Helium-Neon laser light (632.8nm) the sensitivity is typically .4A/W.

The planned loop rate of the control program is 256Hz, so that for the 1024 element array, f is approximately 256000Hz.

The saturation charge for the RL1024G is specified as 4 picocoulombs. Hence,

$$P_{tot} = 4 \text{ microwatts}$$

With a Gaussian distribution laser beam it is difficult to estimate the power of the source necessary to produce the thin beam of light which actually enters the sensor window, but the light profile of the multimode laser can be idealised thus:



ACTUAL IRRADIANCE DISTRIBUTION

APPROXIMATION

If we assume that the beam has been expanded to a width of 40mm and at the point of entering the sensor has a thickness of 7mm (owing to the inevitable expansion characteristics of this type of laser beam), then the beam area is 2.8 square centimetres.

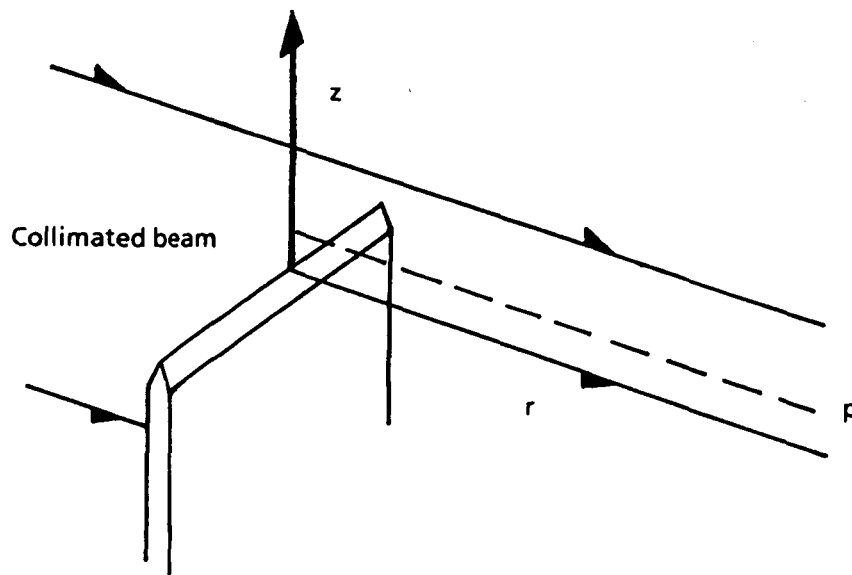
The window of the array has an area of .00645 square centimetres, and so the power of the whole beam must be 1.1mW in order to produce saturation. It may be noticed that, in the absence of a lens to focus the beam on to the window, most of its power is wasted.

The four main sensors are illuminated by a single 8mW multimode laser, whose beam is split into four parts. The various lenses, prisms and mirrors in the optical system produce an attenuation of the individual beams of about 32%. Thus, the chosen source is not excessively powerful.

FRESNEL DIFFRACTION OF AN OBJECT EDGE IN COLLIMATED LIGHT

(The following is freely adapted from Optics by E Hecht and A Zajac, published by Addison-Wesley).

When a semi infinite screen such as the magnetically suspended model is placed in a beam of collimated light, Fresnel diffraction theory may be used to predict the illumination produced at some point beyond the model.



The figure above illustrates the situation. A non dimensional quantity v is used to describe the point of observation P (that is, the location of a sensor pixel) relative to the screen. It is defined as;

$$v = z \cdot (2/\lambda \cdot r)^{\frac{1}{2}}$$

Where the distances z and r are as shown, and λ is the wavelength of the light - equal to 632.8nm for the He-Ne laser.

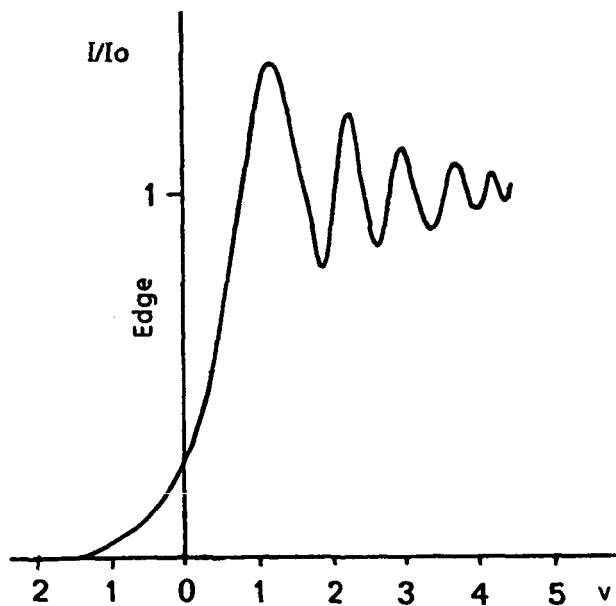
The theory shows that for a value of v , the irradiance I at point P is given by:

$$I = I_0/2 \cdot [(\frac{1}{2} - C(v))^2 + (\frac{1}{2} - S(v))^2]$$

Where I_0 is the undisturbed light intensity.

$C(v)$ and $S(v)$ are the known as the Fresnel integrals, standard functions which have been extensively studied and are tabulated in reference works. If v is zero, i.e. P is directly opposite the

edge, the two functions are both zero and $I = I_0/4$. If the irradiance distribution is plotted for different values of v , the result is thus:



The array saturation level is arranged to be as shown, so that the oscillatory fringes are not seen. If we take the width of the transition edge to be between $v = -1$ and $v = 1.5$, its size can be estimated in terms of pixels for typical model to sensor separations.

For the axial sensor, r is about 150mm for the model at zero incidence.

Hence for	$v = -1.5$	$z = -.327\text{mm}$
and for	$v = 1.0$	$z = .218\text{mm}$

Thus the total width is .54mm or about 21 pixels.

The separation between the model and the four main sensors will be somewhat larger, and so the spreading of the edge will be correspondingly greater.

TABLE 1

COLLIMATION TESTS OF DIODE ARRAY

Model is a brass rod 373 thousandths of an inch in diameter. All measurements are in pixels.

Distance to First Edge	Object Width - model 0" from array	Object Width - model 5" from array
7	382	377
20	379	378
40	379	377
60	379	378
80	379	376
100	379	376
120	379	375
140	378	376
160	378	376
180	379	376
200	378	376
220	379	375
240	378	376
260	378	377
280	378	376
300	378	377
320	378	375
340	378	376
360	379	377
380	378	376
400	378	376
420	379	377
440	378	377
460	379	376
480	378	377
500	378	377
520	378	377
540	378	377
560	379	378
580	379	380
600	378	380
620	379	379
640	378	380

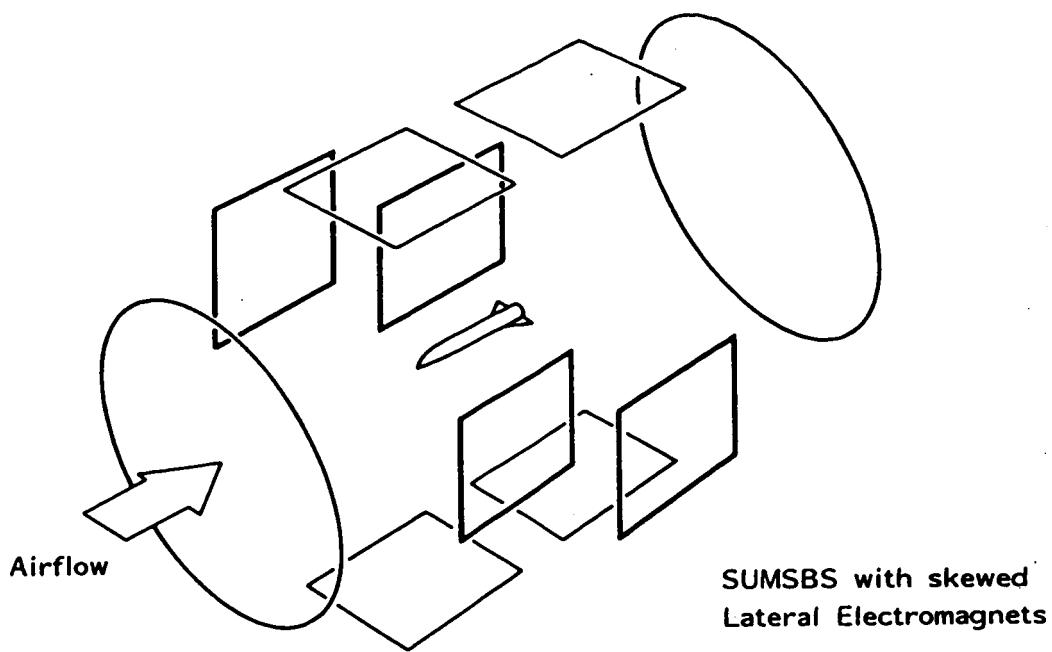


FIGURE 1 Schematic of electromagnet array

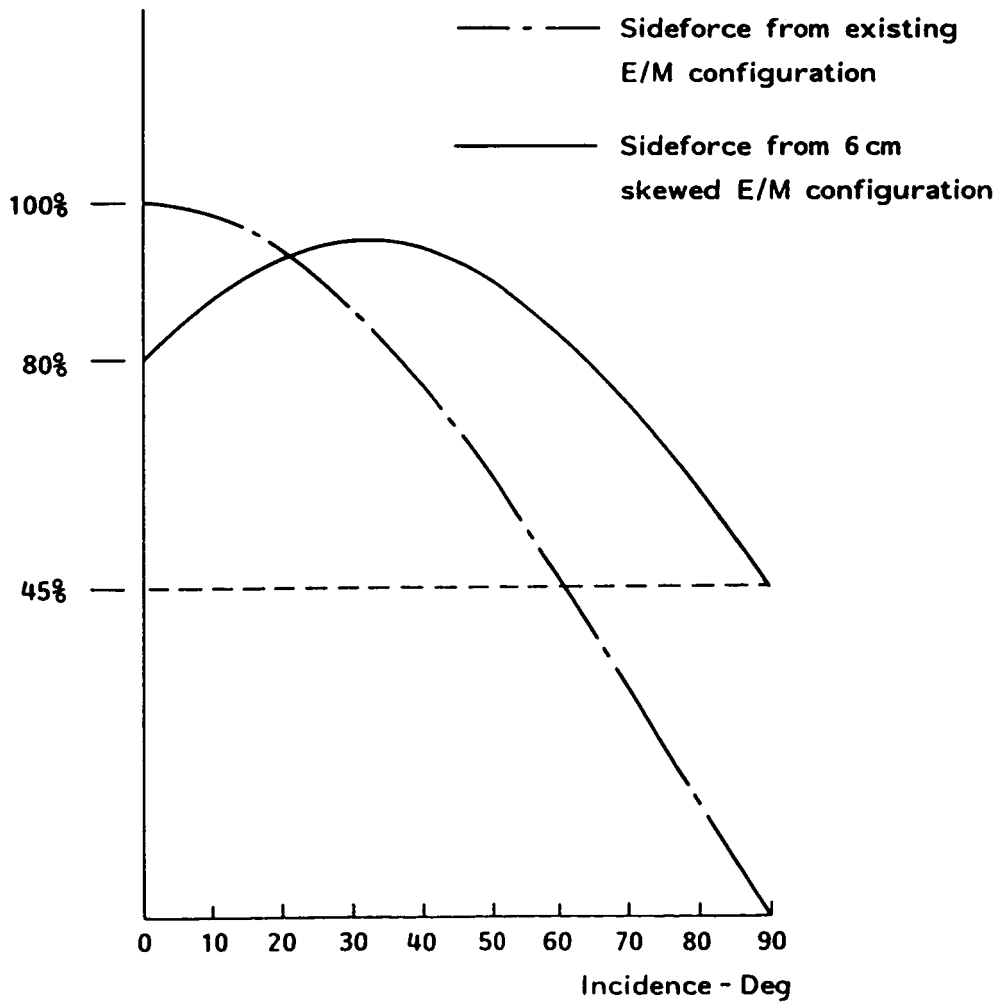


FIGURE 2 Generation of sideforce

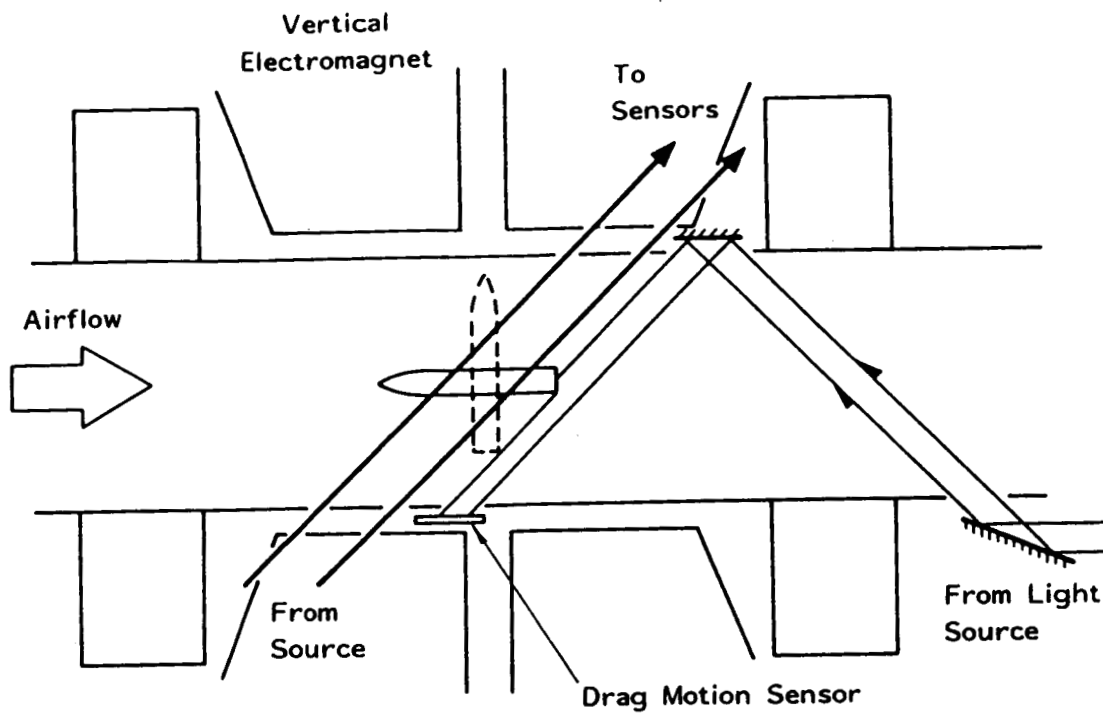


FIGURE 3 Side view of SUMSBS to show Light Beam Arrangement

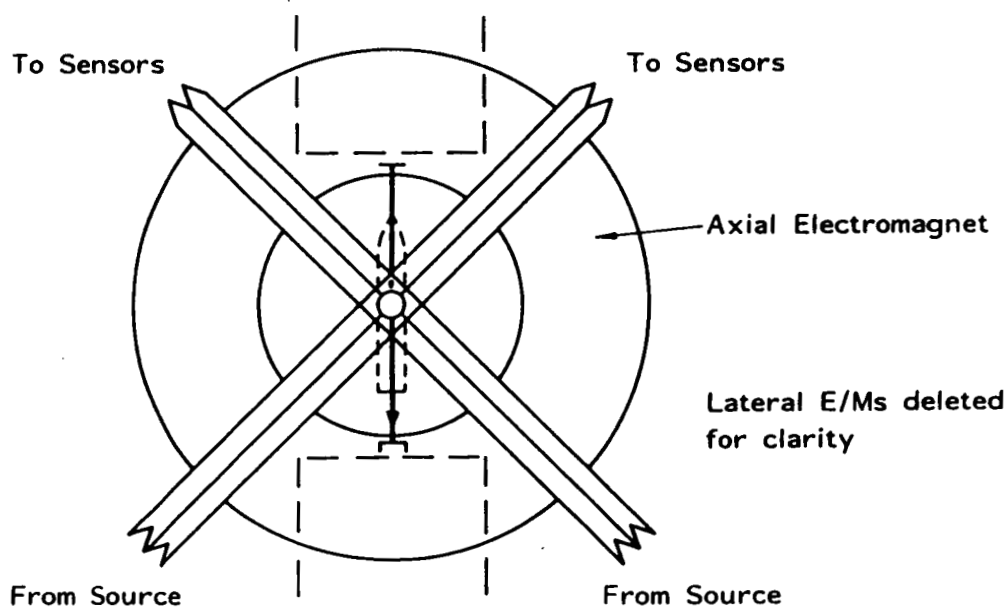


FIGURE 4 View from front of SUMSBS to show Light Beam Arrangement

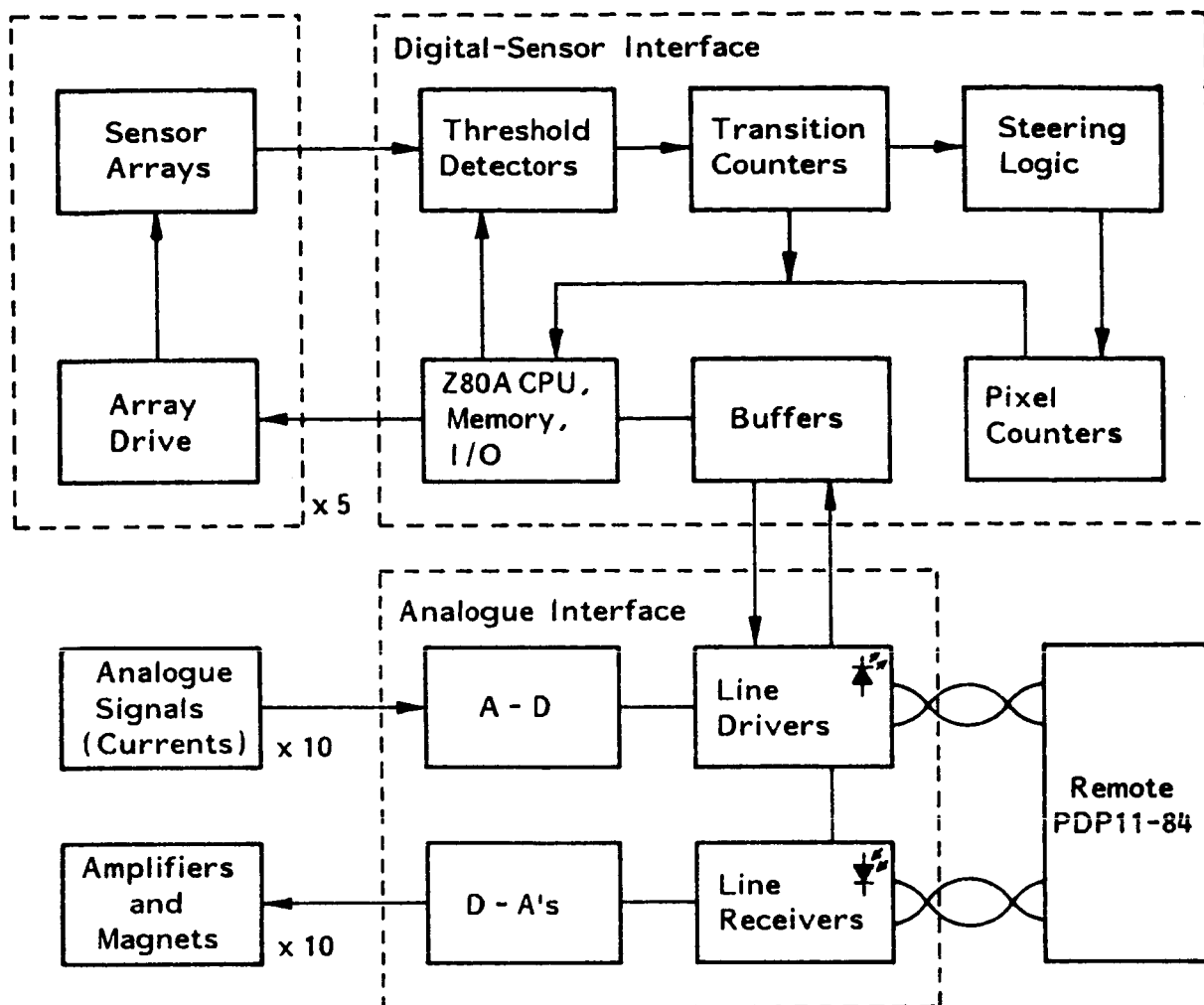


FIG. 5 SIMPLIFIED BLOCK DIAGRAM OF M.S.B.S. WITH PHOTO-DIODE ARRAY CONTROL.

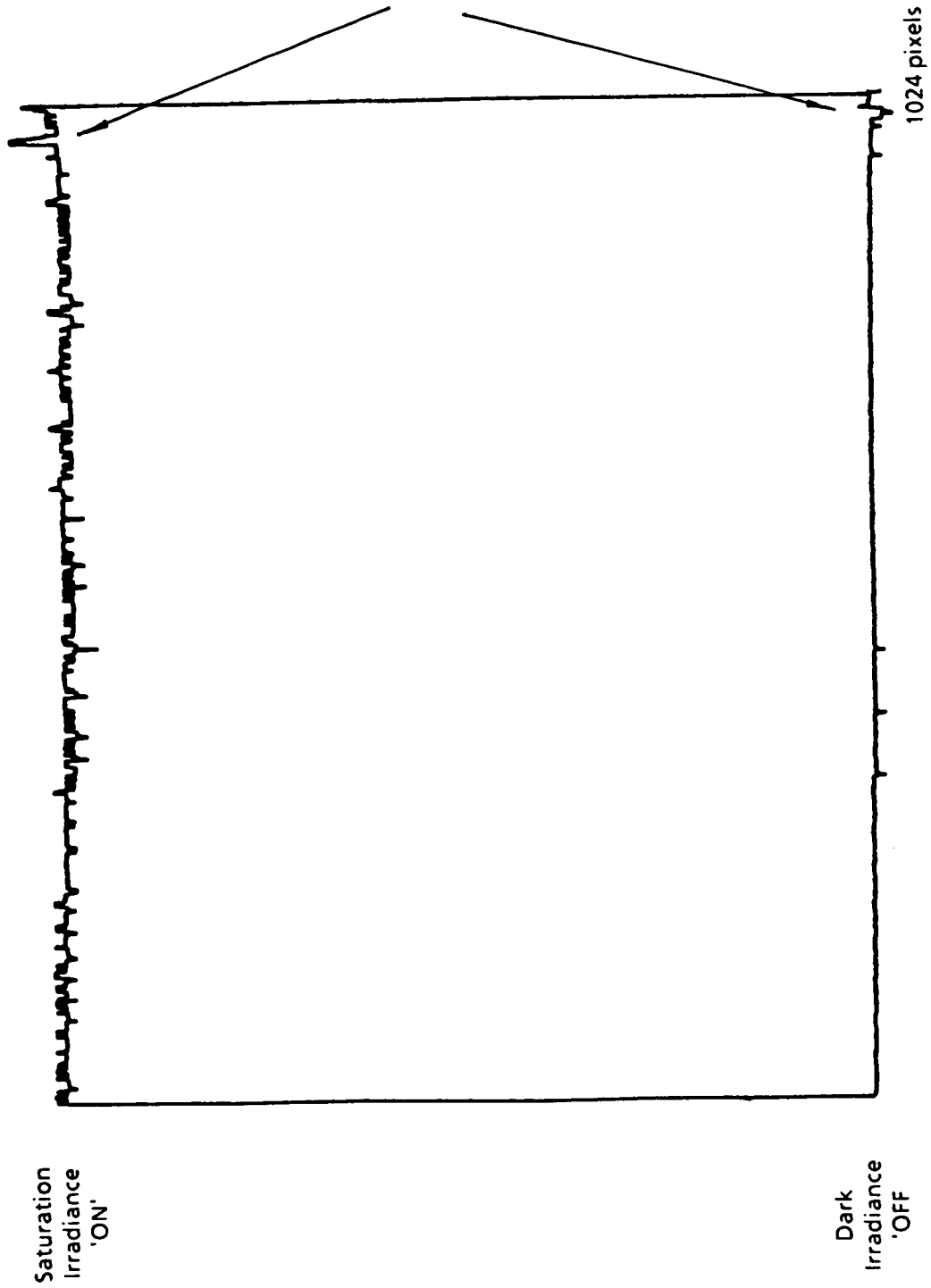


FIGURE 6 Composite Sensor Video Signal - With and Without Laser Illumination

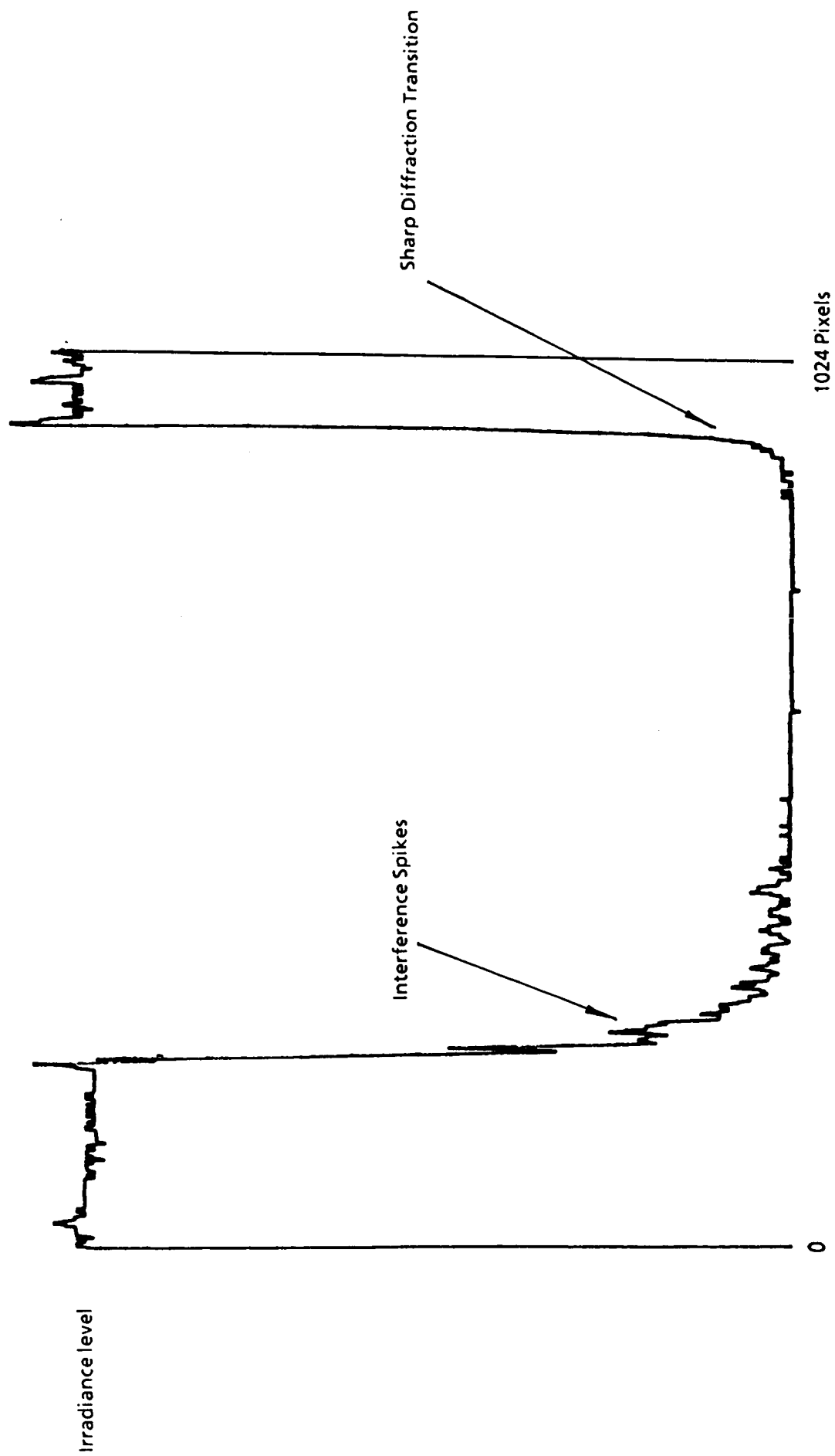


FIGURE 7 Two Edge Events - Sensor installed in SUMSBS

DIGITAL SENSOR CALIBRATION

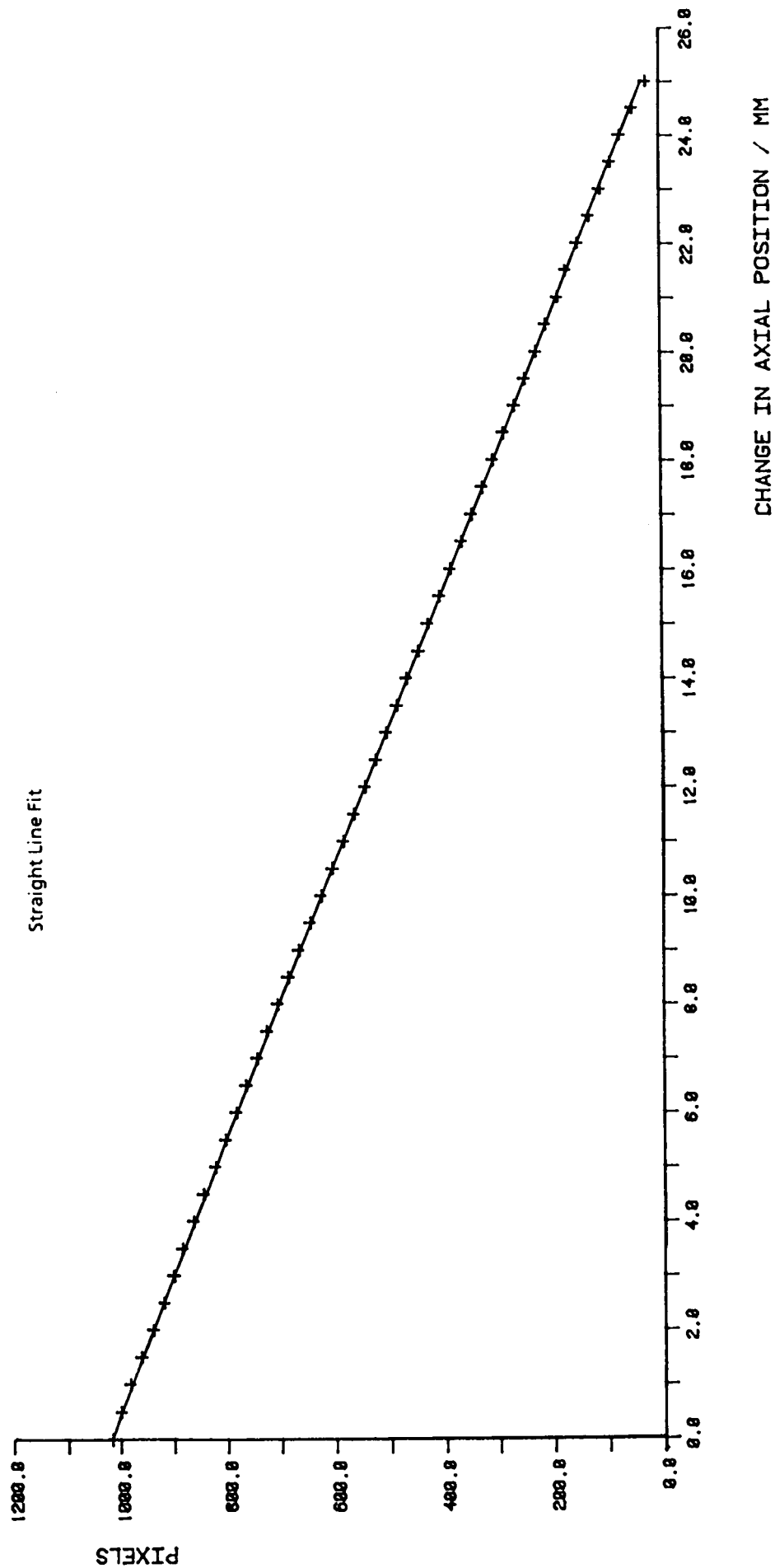


FIGURE 8

ANALOGUE SENSOR CALIBRATION

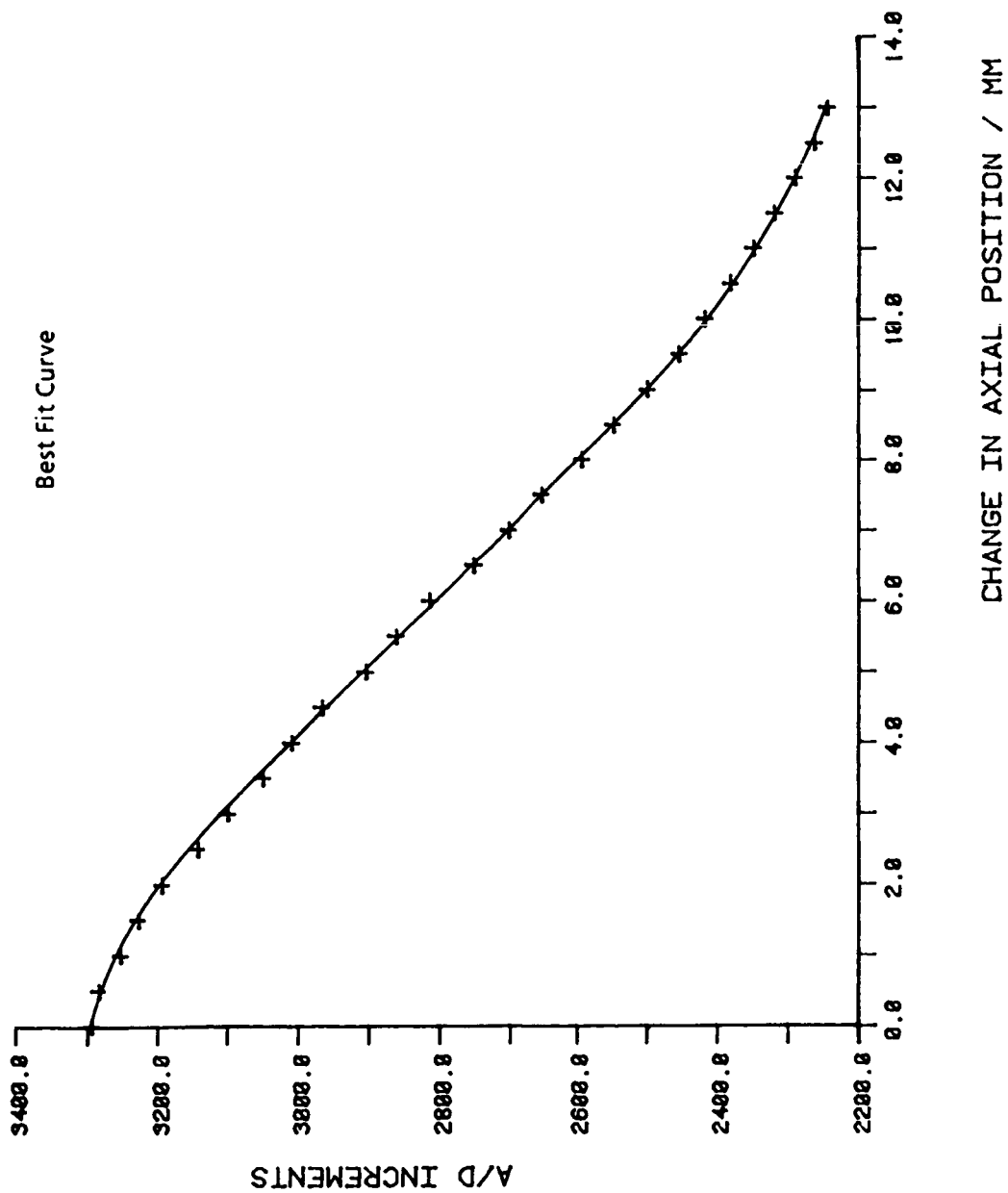


FIGURE 9

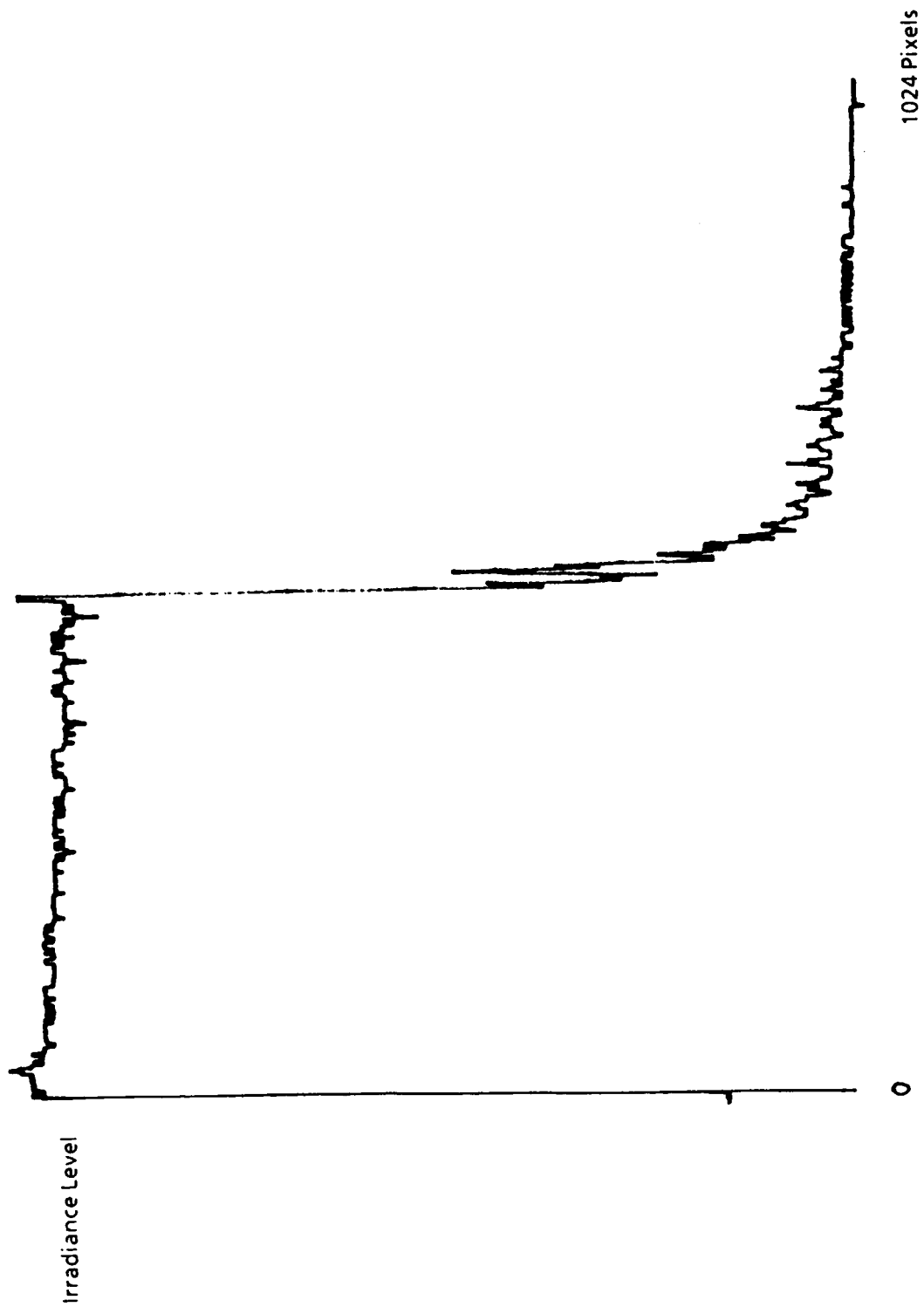


FIGURE 10 Video Signal - Model in Suspension

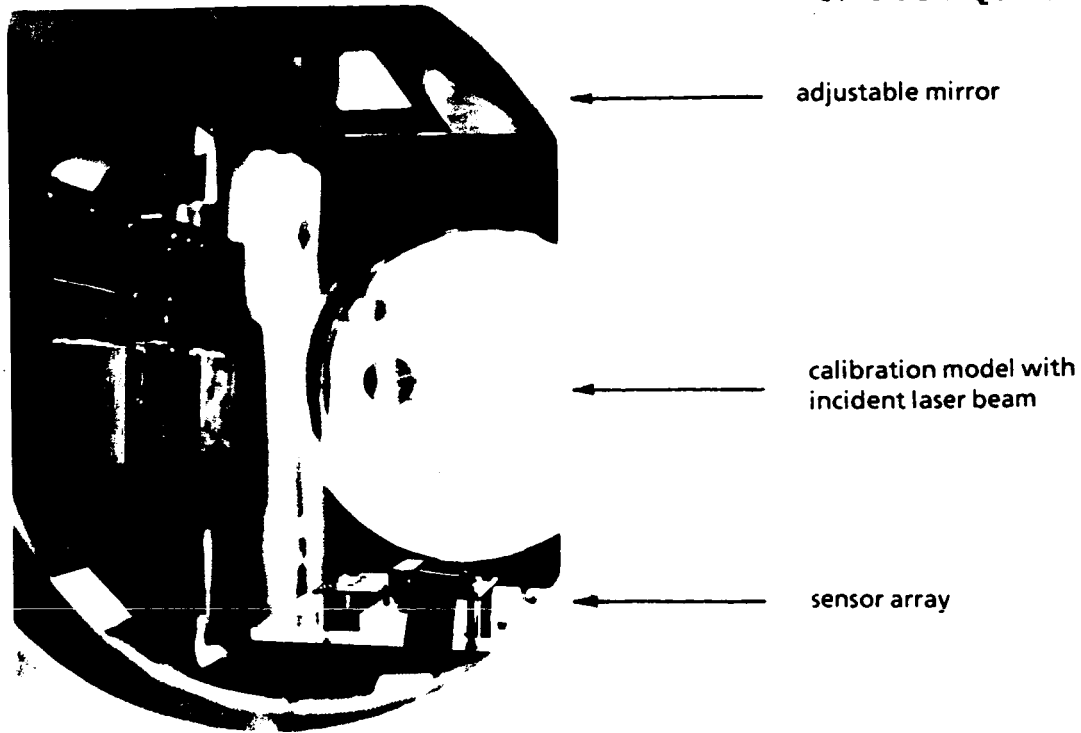


FIGURE 11 View from rear of MSBS with model in suspension

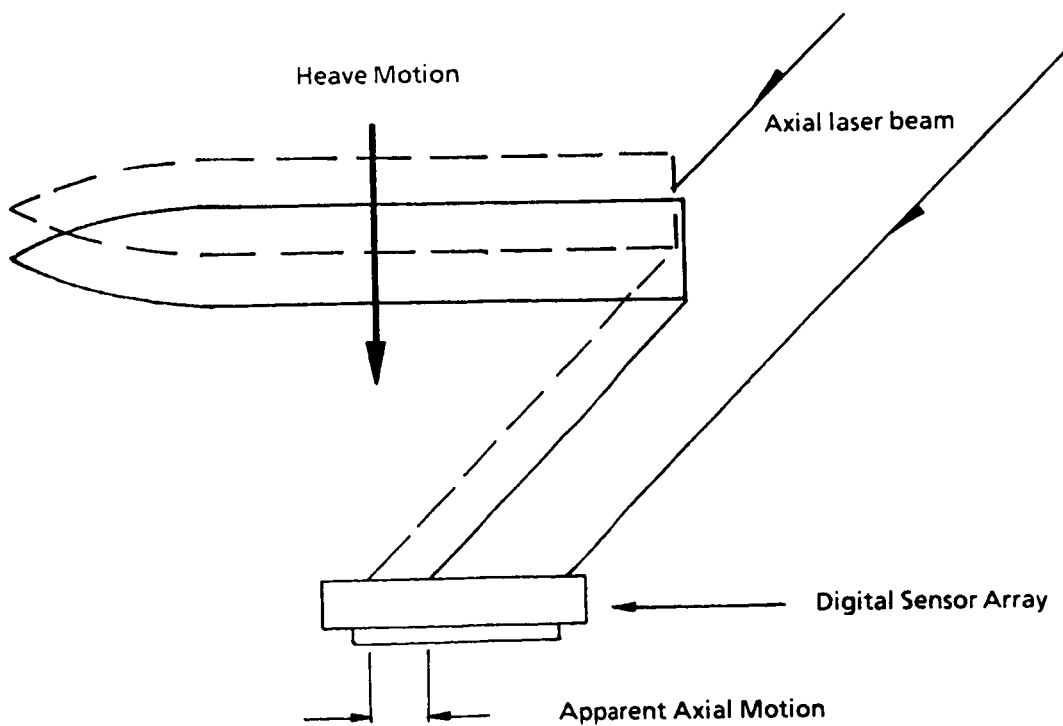


FIGURE 12 Coupling of axial sensor to heave motion

FIGURE 13 AXIAL SENSOR OUTPUT - REQUIRED

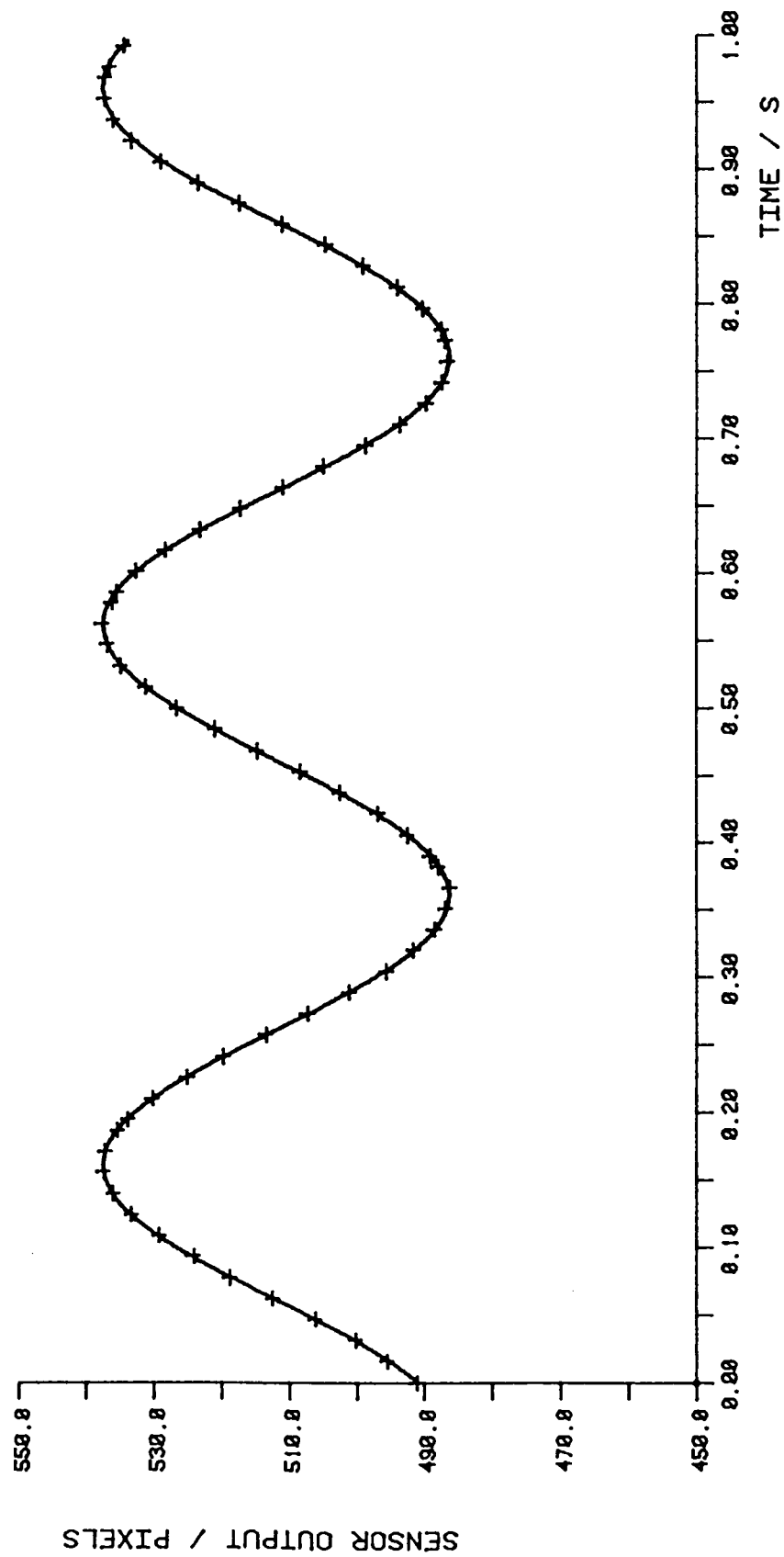


FIGURE 14 AXIAL SENSOR OUTPUT - ACHIEVED

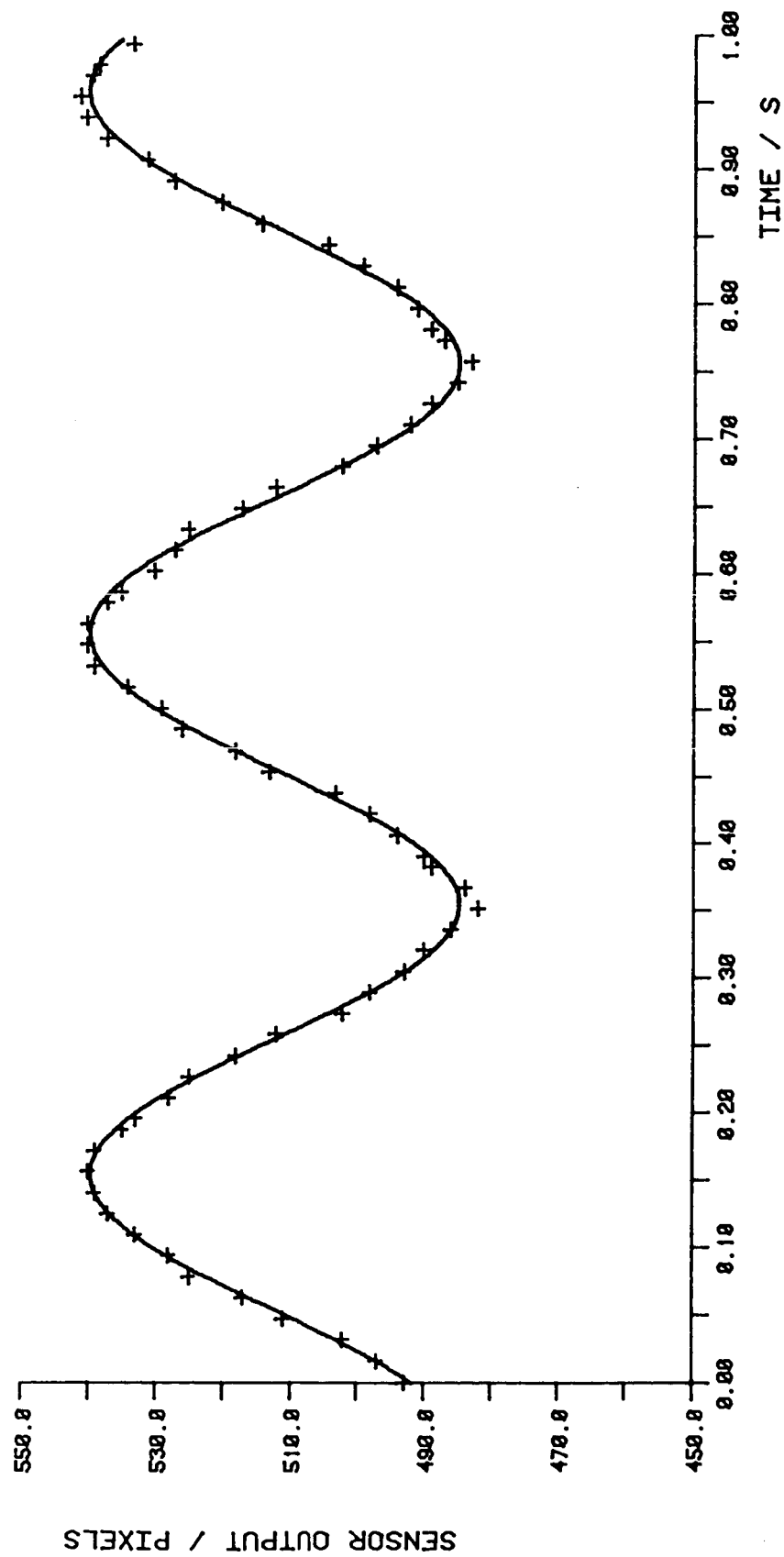
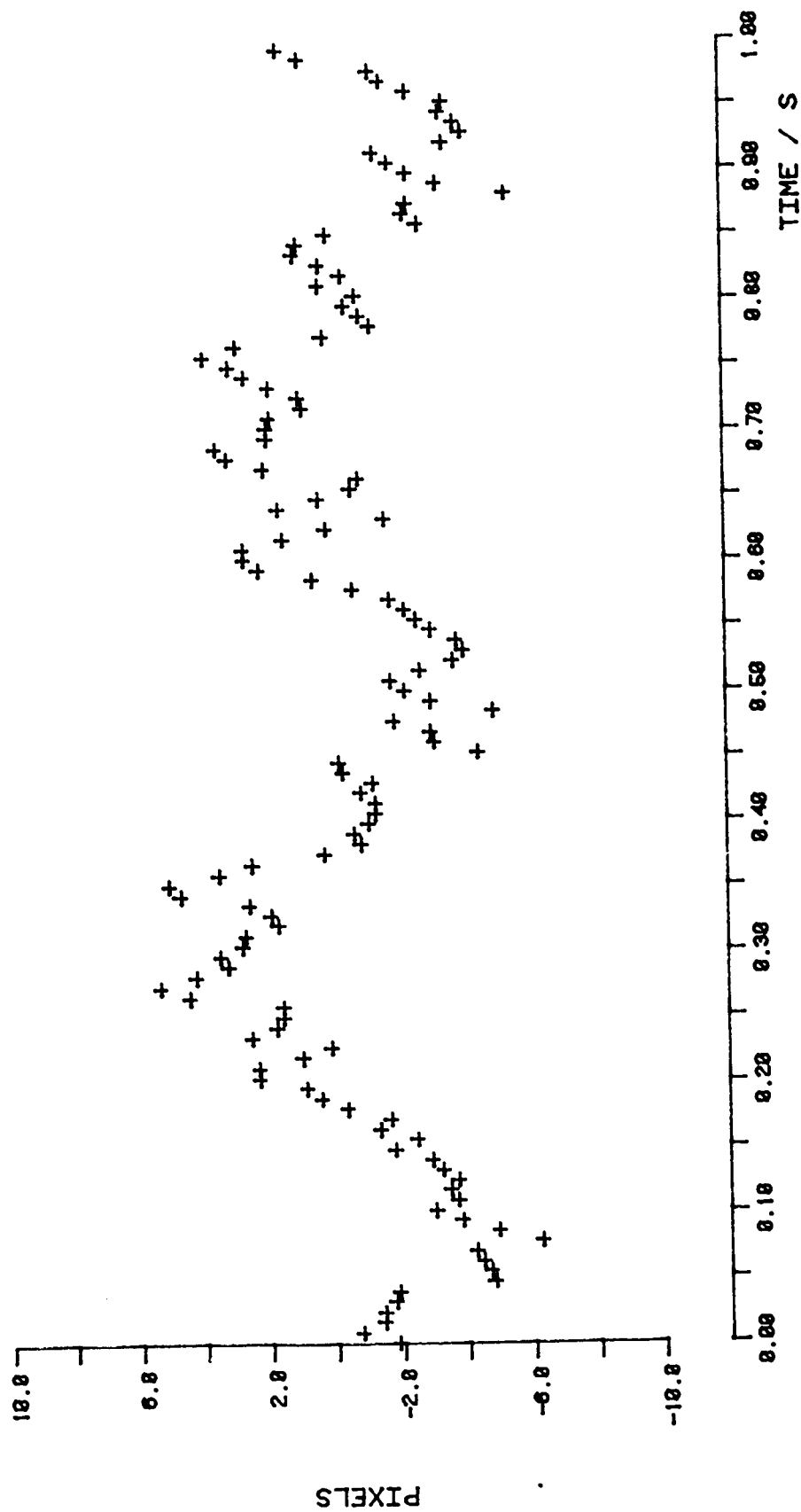


FIGURE 15 AXIAL SENSOR OUTPUT - ERROR



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15. Supplementary Notes Langley Technical Monitor: Richmond P. Boyden Progress Report, 1/86-3/87					
16. Abstract An all digital five channel position detection system is to be installed in the Southampton University Magnetic Suspension and Balance System (SUMSBS). The system is intended to monitor a much larger range of model pitch attitudes than has been possible hitherto, up to a maximum of 90° angle of attack. It is based on the use of self-scanning photodiode arrays and illuminating laser light beams, together with purpose built processing electronics. The principles behind the design of the system are discussed, together with the results of testing one channel of the system which was used to control the axial position of a magnetically suspended model in SUMSBS. The removal of optically coupled heave position information from the axial position sensing channel is described.					
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